Novel Gaits for a Novel Crawling/Grasping Mechanism

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Abstract

A novel, miniature robot designed to use its two arms for both manipulation and locomotion is described. Intended for military and civilian surveillance and search-and-rescue applications, the robot must be small, rugged, and lightweight, hence the desire for dual-use. The robot consists of two, three-degree-of-freedom arms that can stow completely inside the 75 mm diameter cylindrical body for ballistic deployment. Its design is loosely biologically inspired, but heavily constrained by sponsor demands. This paper describes the mechanism and design motivation as well as three novel locomotion gaits and a fourth conventional gait.

1 Introduction

The design of this small robot was biologically inspired in the sense of vague resemblance to biological organisms [1]. This is in contrast to the work of Beer et al [2], for example, in which biological organisms are rigorously studied and relevant lessons are adapted to mechanisms, or Pratt et al [7], for example, in which biological mechanisms are emulated. Rather, I took inspiration from mice, raccoons, and insects and melded them with the decidedly non-biological constraints of my DoD (U.S. Department of Defense) sponsors -- the desire for gun-launchability being a prime example of a non-biological constraint.

The project is aimed at investigating adaptation of very small, rugged, highly resource constrained robots with novel locomotion modes. The target applications are stealthy surveillance and reconnaissance (civilian SWAT teams and the military) and search and rescue after cataclysmic events (natural disasters or major military engagements).

Our primary design is a 40 mm diameter cylindrical robot that is 110 mm long. This robot [15], shown in Figure 1, uses two modes of locomotion: rolling and hopping. Unfortunately, it possesses no ability to manipulate (other than pushing). While manipulation is not required for surveillance, it could aid in "active camouflage" for improved stealth and in active path clearing for search-and-rescue. It also opens up many possibilities for additional missions.

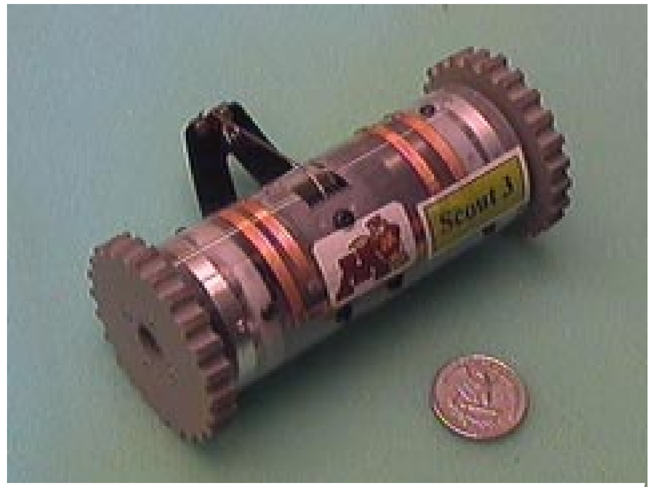

Figure 1: An example of the primary "Scout" mobile surveillance robot.

The resource constraints prevent merely adding arms to the existing "Scout" robot. Every cubic centimeter of mechanism would displace approximately 420 mW-hr of battery power. (For comparison, the CPUs consume around 40 mW while wheeled locomotion consumes from 180 - 600 mW, depending on terrain.) Instead, I chose to design a new robot based on dual-use: arms that serve as both manipulators and locomotors.

The dual-use concept was inspired by raccoons and some insects that use their legs as manipulators. This makes for efficient use of mechanisms, but dual-use generally implies sub-optimality for either use. Due to our space and power constraints, "mechanism efficiency" is of greater concern. Although I'm not aware of any biological creatures that normally possess only two limbs and drag their bodies along the ground, as in the robot described here, insects have been demonstrated to adapt to the loss of limbs.

This paper focuses on the design of the "TerminatorBot" mechanism and the novel (and conventional) gaits that it uses for locomotion. The aspects of adaptation of those gaits to varying terrain are currently under investigation and will be presented when comparative results are available.

2 Prior Work

Mobile manipulation is an area of research that has not been extensively addressed in the robotics community. Manipulators have been placed on mobile robots before (in fact, commercial offerings from Nomadic Technologies and RWI include various "manipulators" as options, including PUMA robots), but they have generally been treated disjointly. Sandia, for example, has put Schilling arms on a variety of platforms for teleoperation in hazardous environments (e.g. [8]). Carriker, et al integrated the path planning of low-DoF subsystems, but motion operations and design for each were treated separately [3]. Khatib has done significant work in integrating the motion control of arms and mobile bases through the Operational Space formulation [6], but has not performed visual servoing nor are the mechanisms dual-use. Brachiation robots, which use arms for locomotion by swinging like a gibbon, have also received some study (e.g. [9]), but current mechanisms are incapable of manipulation.

A few robots have been considered with dual use design. SM^2 and DM^2 at Carnegie Mellon ([12] and [13], respectively) and PolyPod/PolyBot at Stanford/Xerox ([16]) are notable examples. SM^2 and DM^2 are symmetric, biologically inspired inch-worm-like robots with grippers at each end. The robots are designed to walk around the outside of the space station to perform repair and inspection tasks. PolyPod is a modular serpentine manipulator of many similar joint modules designed with both manipulation and locomotion in mind.

Hirose's snake-like robots [4] have been investigated for both locomotion and manipulation with great success (and complexity). These are also clearly biologically inspired, as well. Several additional summaries of work on biologically inspired robotics (such as [1]) are well known to AMAM conference attendees.

3 Target Applications

With its reconfigurable payloads and dual locomotion modes, the Scout robot pictured in Figure 1 is quite capable. Rolling is fairly power efficient and hopping enables it to overcome obstacles, which are common for a robot only 40 mm tall. Unfortunately, while the hopping is required for practical mobility, it is rather time and power inefficient due to the inefficiency of the winch mechanism. Navigational certainty is also very low for hopping. The distance and direction of travel is poorly known and orientation in the plane upon landing is completely random.

Its small size and stealth are useful for military and civilian uses. As mentioned, equipped with a camera or microphone Scouts could be used in search-and-rescue operations following natural disasters (e.g. earthquakes) or terrorist actions (e.g. Oklahoma City bombing). There is also potential interest from civilian SWAT teams in hostage situations and police standoffs. These are natural military uses, as well, particularly in urban warfare environments that involve civilians. Surveillance robots of this size could be carried and deployed by warfighters, keeping the warfighters out of the line of fire and minimizing the risk of civilian casualties in the "heat of the moment."

With vibration detecting payloads, Scouts can be deployed along a roadside to discretely monitor traffic for unique vibration signatures indicating heavy equipment or large troop movements. Finally, it has been suggested they could be used to carry small distributed explosive charges that can be amassed to sufficient volumes through their numerosity. This can serve for demolition of specific targets or detonation of land mines or other unexploded ordnance.

While the Scouts' dual locomotion modes are necessary to achieve many of these missions in real environments, there are concerns they may be inadequate for particular scenarios, hence the investigation of alternate designs. For example, the Scouts would be most useful in search-and-rescue operations in which the damage is too severe and constricting to send in dogs (which arguably will be superior to robots in sensing for the near future). But large amounts of rubble within extremely cramped spaces may thwart both locomotion modes of the Scouts (too much rubble to roll, too little headroom to hop). A crawling robot such as TerminatorBot could fill this niche in which available headroom is, on average, just a few times the rubble size.

In surveillance tasks, it is desirable for the robot to conceal itself. The Scouts will only be able to make use of existing open spaces such as underneath furniture. A robot with manipulators could actually pull objects over itself, creating its own cover and enhancing its stealth. A miniature, telescoping pan/tilt unit has been developed to facilitate such stealthy surveillance, too [14].

The idea of many small robots amassing a useful charge from small, insignificant explosives has been suggested by researchers in a number of scenarios. The main problem with this idea is that the efficiency of explosives is highly dependent on their placement. A bunch of mobile robots with no ability to manipulate would amass a rather inefficient bomb. Just one or two robots with the ability to locomote *and* manipulate could carefully place the charges, demanding many fewer trips to achieve a given objective.

Finally, in many of these scenarios, the ability to dig or burrow in light soils is be beneficial. This could provide camouflage during surveillance, additional access during search-and-rescue, and an alternate detonation means during de-mining.

4 Mechanism Design

The robot consists of a cylindrical body with two 3-degree-of-freedom (DoF) arms that can fully stow inside the

Figure 2: CAD rendering of TerminatorBot in the stowed configuration.

body (Figure 2). The ultimate goal is to fit the 40mm diameter form factor of a launchable grenade, but the current prototype is approximately two times oversize with a diameter of 75 mm and maximum reach of each arm of 170 mm.

Two gearmotors within the body drive a 2-DoF shoulder joint through a differential. This arrangement couples the torque of both motors through the same axis of rotation for pure motions around the principal axes. Encoders on each motor provide position feedback for positioning link 1. The gearmotors have a relatively low ratio of 17:1, but an additional reduction stage in the form of a 15:1 worm gear boosts the total gear ratio to 255:1 and prevents back-driving the motors. Back-drivability is bad for power conservation in this case.

The first link is 100 mm in length and 23 mm in width, allowing the inclusion of the gearmotor and encoder for the third joint within. A right-angle gear arrangement transfers torque to a traditional 1-DoF elbow joint that drives the 70mm second link. Incorporated into the joint are torque sensors for direct measurement of joint torque at the point of application. Force/torque sensing is incorporated for use during manipulation of objects and also to enable servoed back-drivability of the gear train.

The torque sensors include a number of important design features to increase their utility. Each sensor wheel (see Figure 4) is designed to provide two axes of force/torque. A traditional torque sensor (see cross-section in Figure 5) consists of four to eight radial flexures arranged with regular spacing about the center point [10]. By biasing the distribution of flexures toward a single diameter, as in Figure 5, the sensor is made more sensitive to forces along **F**. As in a multi-axis wrist force/torque sensor, the flexures can be used to sense multiple components. But a common problem with multi-axis sensors is maximum load capacity is dominated by torques, which multiply quickly. To combat

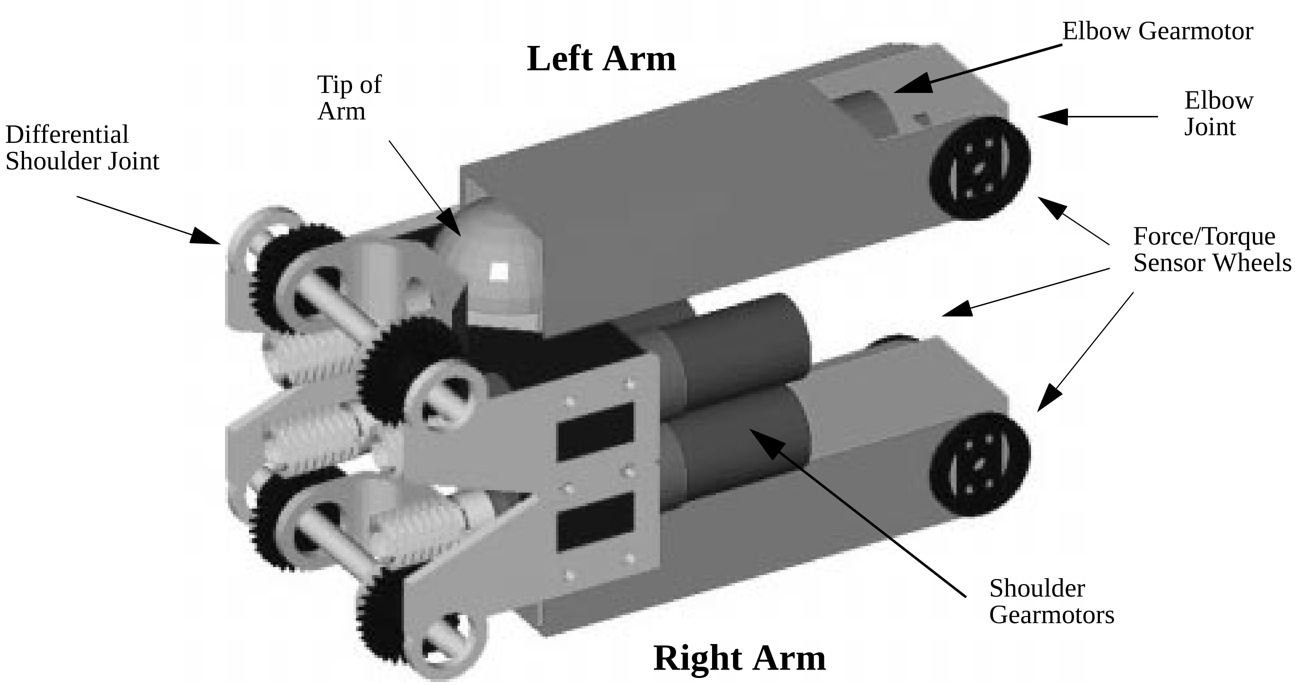

Figure 3: Internal parts of the TerminatorBot in the stowed configuration. Bearings and some other parts are not illustrated.

Figure 4: 2-DoF force/torque sensor wheel for elbow joint.

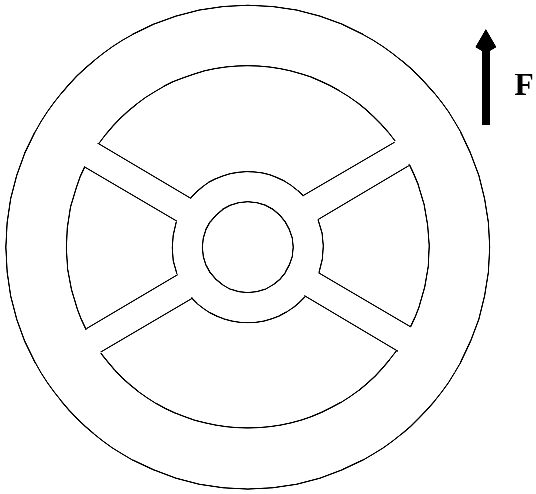

Figure 5: Cross-section of "traditional" torque sensor with radial flexures (although irregular flexure spacing is "non-traditional" - see text).

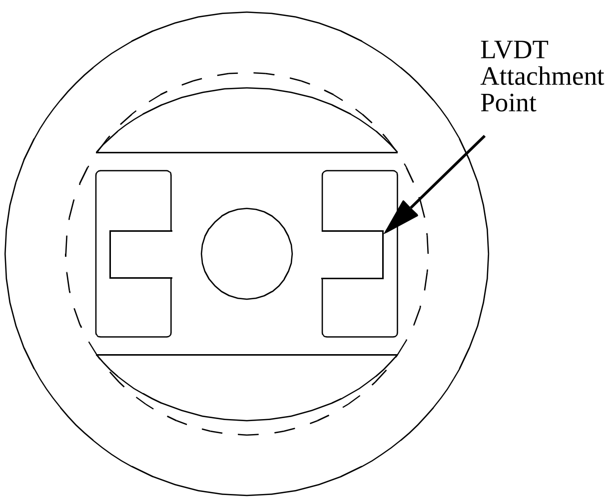

Figure 6: Cross-section of the force/torque sensor wheels used on TerminatorBot.

this problem, the flexures are placed off the radii and perpendicular to the force (Figure 6). For a given flexure dimension, this diminishes the torque sensitivity and increases the force sensitivity, making the response more isotropic.

The use of strain gages on such a small device (The flexures are only 2 mm wide and 2.5 mm long) would present manufacturing problems and the compressive strains introduced by the off-radii flexures would inject noise. Instead, LVDTs (linear variable differential transformers) are mounted between the hub and the link to sense pure deflection as in [5]. LVDTs are insensitive to the noise strains experienced by the flexures and, due to their high frequency carrier wave excitation, are more immune to electrical noise produced by the motors and other sources.

Finally, two sensor wheels are employed on each joint, one on each side. This allows the measurement of a third axis of force at the manipulator tip, complementary to the other two components. This is somewhat problematic because the sensors are not collocated and it is impossible to disambiguate a force at the tip from a transverse torque. Nonetheless, the additional force axis will be valuable during manipulation as the manipulators do possess the ability to move out of plane and it is unlikely that transverse torques will come into play during manipulation of objects (which is the only time precise measurements are required).

The tips of the arms are hemispherical shells that serve a dual purpose. The concave side is claw-like and is useful for traction during locomotion and even for digging in very light soils, such as sand. When manipulating objects, the arms will flip 180 degrees, exposing the convex sides to one another. These surfaces are like fingertips and provide a fixed center of rotation for objects moving across the spherical surface. Coupled with the force/torque sensors, this can be modeled as a passive, but sensable, fourth joint on each arm during manipulation.

The assembled prototype is shown in figures 7 and 8. The arms of the prototype are 105 grams each and the body is 440 grams excluding batteries and CPU, for a total of 650 grams in mechanism alone.

5 Locomotion Gaits

Novel mechanisms often suggest novel and mechanism-specific gaits, as was the case with PolyPod [16]. There are four proposed classes of locomotion gaits for use on TerminatorBot: swimming gaits, narrow-passage gaits, bumpy-wheel gaits, and a dynamic rolling gait. All the gaits are used on dry land, but the "swimming gaits" are so named because of their similarity to two-armed swimming strokes. These are the "conventional" gaits, characterized by stances with the arms slightly splayed out to the sides and a full stride through much of the range of motion of the shoulder joints (Figure 9). To clarify operation on the target mechanism. Figure 10 contains a sequence of images of the TerminatorBot "swimming."

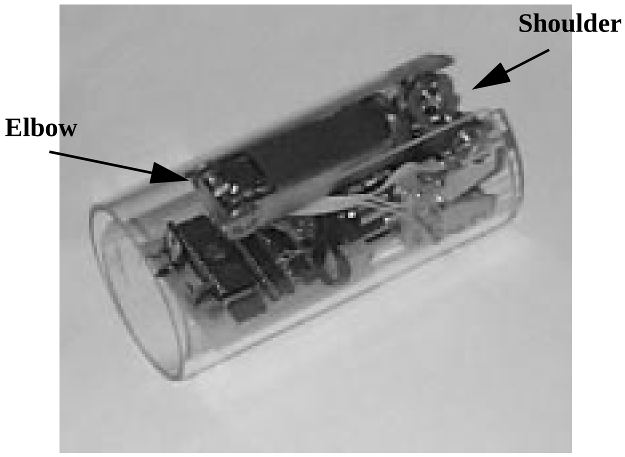

Figure 7: Assembled TerminatorBot in stowed configuration.

Figure 8: Assembled prototype with microcontroller for joint control in deployed configuration.

The narrow-passage gait is a novel gait that makes profitable use of the differential shoulder joint and unique ability of the first link to rotate around its principal axis. Motivated by the ability of mice, which can penetrate any opening through which they can pass their head, the robot can gain passage through openings that are no wider than the body itself (provided navigational capability is sufficiently precise). The motions of the limbs require zero lateral clearance. (Although required vertical clearance is slightly

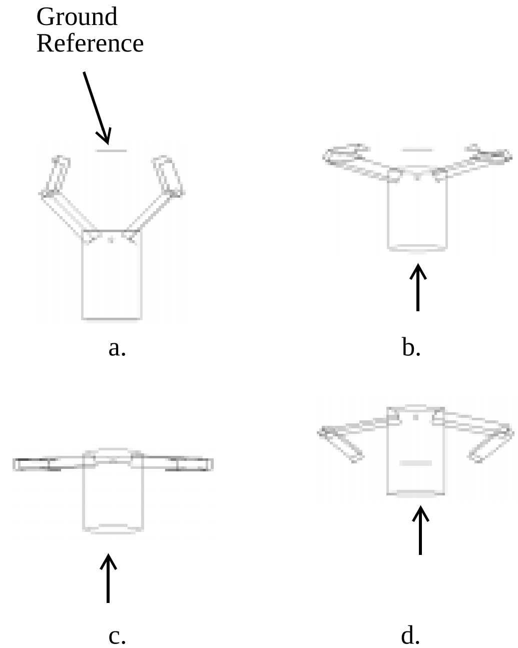

Figure 9: Simulation of an example swimming gait. (top view)

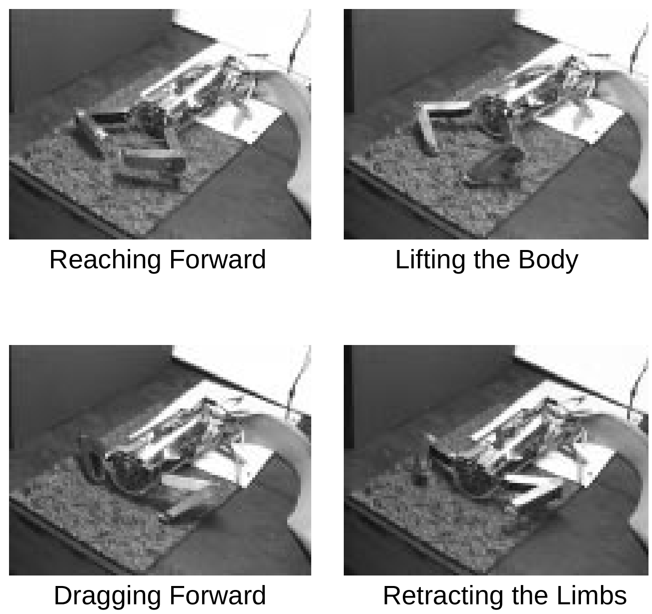

Figure 10: Implementation of a swimming gait on the prototype robot.

larger than one body diameter.) Illustrated in Figure 11 with both top and side views, motion is effected entirely forward of the robot’s body as it pulls itself along. Again, Figure 12 illustrates the narrow-passage gait on the prototype.

The bumpy wheel gait is another novel gait that makes use of the ability of the differential shoulder to rotate 360 degrees. As Figure 13 indicates, the arms “roll” like broken

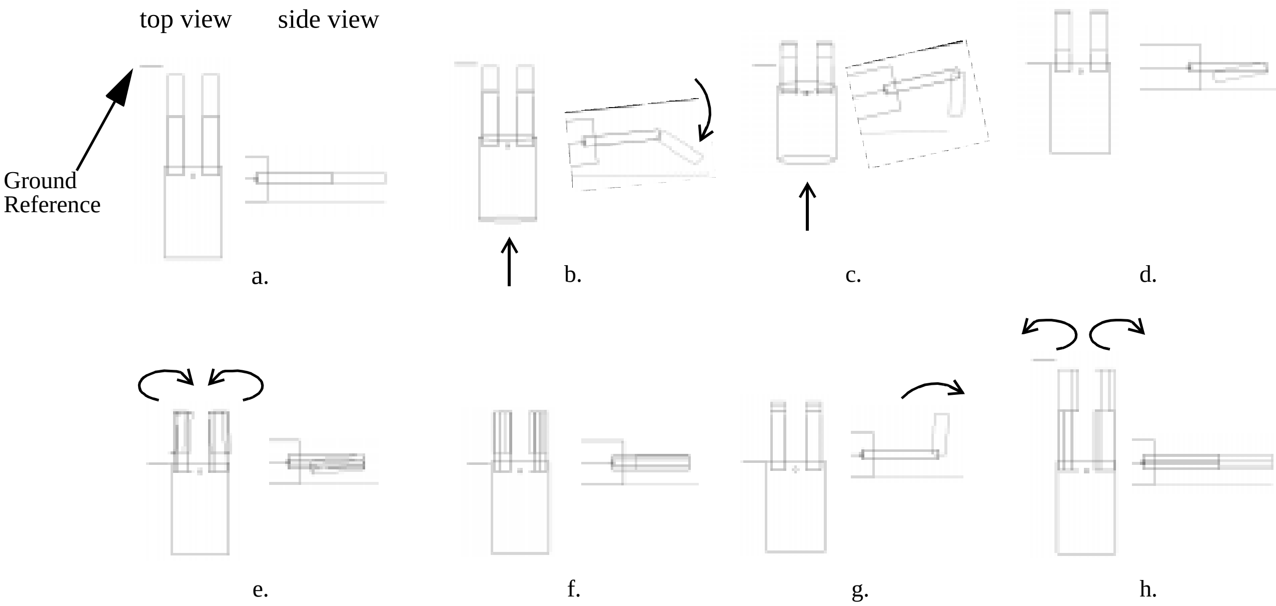

Figure 11: A narrow-passage gait. The robot's arms start a stride outstretched in front of it. In a. through d. it pulls itself forward with the elbow joints, while in e. through d. it rotates the arms back into position to begin another stride. The end effector (claw) is not drawn, hence the space between the robot and the ground line.

wheels to move the body forward. This is the most powerful gait as all four shoulder motors are coupled to drive the body forward and forces on the elbow joint are absorbed by the structure. In fact, the current prototype does not have slip-ring electrical contacts, so continuous rolling of joint two is not permitted. Still, the bumpy wheel gait can be implemented by rolling 180 degrees, straightening the elbow, and rotating back to the start position.

The body-roll gait is quite different from the others. Rather than being a kinematic approach to dragging the robot to its destination, this proposed locomotion gait uses dynamics and an assumption of a smooth, level surface. Since the arms can tuck inside the cylindrical form of the body, the "can" is able roll, once it gets going. The body-roll uses a single arm to build angular momentum by swinging it perpendicular to the roll axis. The other arm tries to prevent

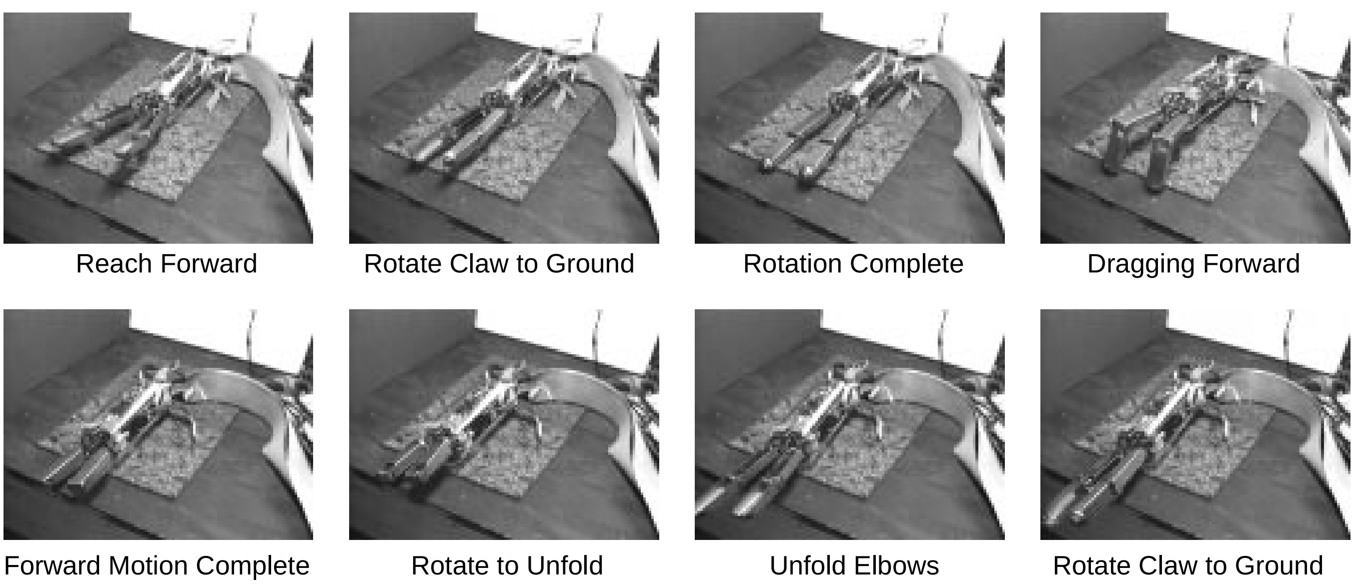

Figure 12: Implementation of the narrow-passage gait on the protptype robot.

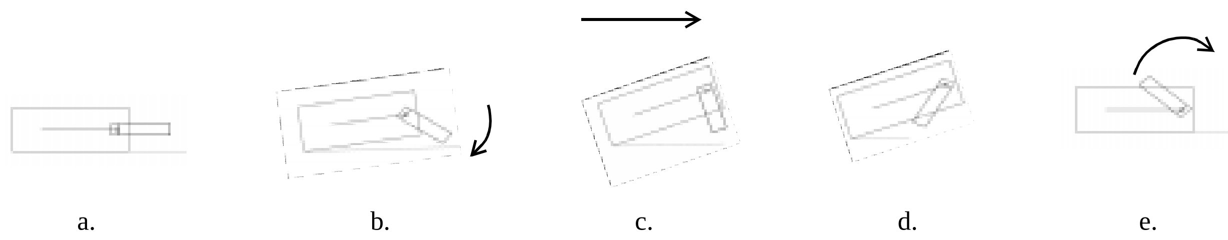

Figure 13: A bumpy wheel gait (side view). The torque of all four shoulder motors is coupled to produce forward motion (toward the right). Again, the claw is not drawn.

kick-back during the swinging motion. The swinging arm then folds up, into the body, causing a reactionary torque that rolls the body forward or backward. In order to effect turns, a swimming gait would most likely be used to reposition the body. The use of an accelerometer for gravity sensing would provide odometry.

The body-roll gait can be achieved using one arm, but one-arm gaits, in general, are another category that could be based on variations of the other four gaits. These can be implemented as emergency homing measures in the event of an arm failure.

It can be argued that these gaits are inefficient compared to wheels or even legs that are optimized for locomotion. This may be true. Dual-use generally implies non-optimal for both uses. The motivation behind this design is that both locomotion and manipulation are required to maximize utility of the robot as a whole, but size and ruggedness constraints prohibit redundant systems optimized for their specific purposes. In this sense, we are trying to optimize the robot as a whole, rather than specific parts.

6 Acknowledgments

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7 References

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